Coherent Communication Link Using
Diode-Pumped Lasers

Final Report for Contract
NAS5-30487

Submitted to

NASA Goddard Space Flight Center

by

Thomas J. Kane
Richard W. Wallace

Lightwave Electronics Corporation
1161 San Antonio Road
Mountain View CA 94043

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SUMMARY PAGE
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Optical communication between satellites could provide links with almost unlimited bandwidth, using small antennae and moderate transmitted powers. This work made steps toward developing a diffraction-limited, single-frequency, modulated transmitter suitable for coherent optical communication or direct-detection communication. We used diode-pumped, monolithic Nd:YAG nonplanar ring oscillators as the carrier beam. We invented an external modulation technique which can handle high optical powers, has moderate modulation voltage, and which we believe can reach modulation rates of 1 GHz.

Under this contract we built semiconductor-laser-pumped solid-state lasers which have high output power (0.5 Watt) and which oscillate at a single frequency, in a diffraction-limited beam, at the wavelength of 1.06 microns. We also demonstrated a technique for phase-modulating the laser output by 180 degrees with a 40-Volt peak-to-peak driving voltage. This technique can be adapted for amplitude modulation of 100% with the same voltage. This technique makes use of a resonant bulk modulator, so it does not have the power handling limitations of guided-wave modulators.

For Phase II, we propose to use this technology to build an integrated laser/modulator with an output of 0.3 Watts at 1.06 microns and a modulation rate of 1 GBit/Sec. Versions useful for both coherent communication and direct-detection links would be delivered.

This laser/modulator module will be useful for communication between satellites, or from deep space probes to Earth-orbiting stations. Versions of this system operating at 1.32 microns and coupled to single-mode optical fiber will be useful for terrestrial fiber optic communication.

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Results of the Phase I Work

Objectives of Phase I

The goal of the Phase I SBIR effort was to investigate laser transmitter systems which would be appropriate for communications. We were to address both the laser and techniques for modulating information onto the laser output.

The first objective was to build and characterize high-power lasers at 1.06 microns and 1.32 microns. In these tests we used as pumps both a standard 1 Watt laser diode, and also a special 2 Watt laser diode pump. Good results were achieved at the 1.06-micron wavelength. Difficulties with optical coatings led to a null result at 1.32 microns.

The second and third objectives were to couple the output of a single frequency laser into a guided-wave modulator and then study this phase modulation using heterodyne detection. It became obvious early in the contract period that a guided-wave modulator, while useful for the low powers characteristic of optical fiber communication systems, did not answer the needs of NASA for modulators capable of handling powers on the order of 1 Watt. As a result, a bulk modulator with high power handling capability and low voltage requirements was invented and demonstrated.

The forth and fifth objectives were studies of both absorption lines that may be available to use as absolute wavelength references, and of laser materials other than Nd:YAG that could be used for increased channel bandwidth.

Phase I results

High power nonplanar ring lasers

Monolithic, nonplanar Nd:YAG ring lasers can efficiently provide single-frequency power at the wavelength of 1.06 microns. The output power at this wavelength has been limited by the power of available pump lasers. Significant single-frequency output has also been observed at 1.12, 1.32 and 1.34 microns.

In a previous SBIR Phase II contract with NASA JPL, which was completed in April, '89, the greatest amount of single-mode 1.06 micron light produced was 379 mW of TEM_{oo} output power with 947 mW of diode pump power from a special low-divergence 2 Watt diode made by Spectra Diode Labs. This diode laser had a 200 micron emitting aperture. At higher pump levels the ring laser would

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develop higher-order transverse modes. Our best optical efficiency had come using another Spectra Diode Labs experimental low divergence diode with a 60 micron stripe width. Optical conversion efficiency of 59% was achieved. We obtained 310 mW of single-longitudinal-mode output at 1.06 microns from an input of 525 mW of 0.808 micron pump light.

Under this contract, we tried to set new records for single-frequency power from monolithic rings. We used 1 and 2 Watt diodes to pump lasers designed to oscillate at both of the 1.06-micron and 1.32-micron wavelengths of Nd:YAG. We also built laser resonators designed to oscillate at the 1.32-micron wavelengths of Nd:GGG (Gadolinium Gallium Garnet) and Nd:GSGG (Gadolinium Scandium Gallium Garnet).

The 1-Watt pump we used was a standard-product laser diode available from Sony Corporation. This is the laser used in Lightwave's 110-Series Q-switched lasers. Using this laser at a conservative output power level of 835 mW, we achieved 390 mW of single-frequency, TEMoo output at 1.06 microns. Previously, this level of power was reached with an experimental laser from Spectra Diode Laboratories. This experimental diode had very low divergence, and was thus easy to focus to a small spot with standard lenses. The disadvantage of this experimental diode was the very high level of intensity noise, over 10%. Using the Sony standard laser, the noise level was below 1% peak-to-peak.

The technical improvement which permitted us to reach this high output from the Sony laser was better collection and focussing of the diode output. The well-focussed pump beam was matched to the TEMoo mode volume of the laser, and thus did not excite higher order transverse modes.

We used this same, improved focussing system with the 2-Watt experimental low-divergence laser diode from Spectra Diode Laboratories, the same experimental pump used for earlier experiments. With this pump at an output level of 1.7 Watts, 516 mW of single-frequency, TEMoo output was observed. This is a record level of output from a monolithic ring. This laser had a 12.5% peak-to-peak noise level, which is not acceptable for many applications. It appears that the experimental low-divergence diodes from Spectra-Diode Labs, while useful for producing raw output with very high efficiency, have noise problems which make them undesirable for many applications. (We emphasize that there is no noise problem with SDL's standard products.)

Our experiments aimed at reaching high power at the 1.32-micron wavelength were discouraging. We fabricated

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monolithic lasers of three materials: Nd:YAG, Nd:GGG, and Nd:GSGG. One might wonder why we would consider materials other than Nd:YAG, when such good efficiency has been achieved with Nd:YAG at 1.06 microns. The problem with Nd:YAG at 1.32 microns is due to the existence of a laser transition at 1.34 microns with almost exactly the strength as the 1.32 micron transition. Many lasers we have built oscillate at both wavelengths simultaneously. Though there is a single mode at each laser transition, the laser is not single-mode overall. Simultaneous oscillation would only be possible if the cross-section at both wavelengths are very nearly identical. This exact equivalence would result from the particulars of the interaction between the neodymium ion and the YAG host material. Our investigation of other materials was due to the hope that other host materials would not have the near exact equivalence between the two transitions. Thus we obtained samples of Nd:GGG and Nd:GSGG and built monolithic rings from them. We did not use more widely available neodymium hosts such as YLF or YALO because we do not know how to fabricate monolithic rings from materials which are birefringent. Of the crystalline laser hosts we know of, only the garnet family is optically isotropic.

We pumped these monolithic rings with the powerful pumps described above. The crystals lased, but with extremely poor beam quality and high threshold of lasing. The GSGG was better then the GGG, but both were poor. The beams had complex halos and distortions. The output was unstable and noisy even with the quiet, 1-Watt pump. We conclude that the YAG we use is of an optical quality well above what is currently achieved with experimental materials such as GGG or GSGG. This high level of optical quality is needed for low-gain lasers such as diode-pumped lasers. We conclude that without a major effort to improve optical quality, no further effort with materials other than YAG are warranted.

Our work with Nd:YAG at the 1.32-micron wavelength was also disappointing. In order to avoid the dual-wavelength problem of Nd:YAG, we coat the crystals to favor shorter wavelengths, and thus usually suppress the 1.34 micron transition. Sometimes the coating is too short and the 1.12 micron or 1.06 micron transition of Nd:YAG lases. This was the case with the lasers built under this contract. Intended to lase at 1.32 microns, they instead lased at 1.06 microns. We have had these laser crystals re-coated and will test them again. This will not be done in time to include the results in this report.

The primary conclusion of our work is that it is possible to reach an output of 390 mW from a monolithic

resonator in a diffraction-limited, single-frequency laser beam at 1.06 microns, using commercial, off-the-shelf laser diodes. We expect that when we get the coatings right, we will also get good results at 1.32 microns. Other laser materials are not a good bet. Table 1 summarizes our work under this contract related to the construction of single-frequency lasers.

TABLE 1: Monolithic Ring Lasers Built and Tested

Material	Wavel.	Power	Comments
Nd:YAG	1.06	516 mW	High noise, experimental pump
Nd:YAG	1.06	390 mW	Low noise, standard pump
Nd:YAG	1.32	–	Coat error – Lased at 1 micron
Nd:GGG	1.32	30 mW	Bad beam, high noise
Nd:GSGG	1.32	80 mW	Bad beam, high noise

Modulators

For optical communication through free space, it is desirable to use output power levels on the order of 1 Watt. Under this contract we have demonstrated a diffraction-limited, single frequency diode-pumped laser with output of 0.39 Watts and good stability, and 0.52 Watts with increased intensity noise. We believe that 1 Watt will be achieved soon.

Diode-pumped lasers cannot be modulated directly. They need external modulation in order to be useful for information transmission.

There are two types of high-speed modulators which are widely used. The type most often considered for communications use is known as a waveguide modulator. In this type of modulator the light to be modulated is confined to a region of very small cross-section. These modulators need only moderate voltages, and are useful at modulation rates well over 1 GHz. Unfortunately, the standard waveguide modulators are limited to optical powers of a few milliwatts. This is due to the very small dimensions of the waveguide. The very high intensity (Watts per square centimeter) in these small waveguides leads to temporary or permanent optical damage. The losses coupling into and out of waveguide devices are also high, usually between 6 and 8 dB, that is 75% to 85% of the input power is lost. The desirable properties of waveguide modulators are that they only require 5 to 10 volts for maximum depth of modulation and that they can support modulation frequencies of a few GHz.

The oldest type of high-speed modulator is known as a bulk modulator. A bulk modulator is simply a piece of electro-optic material with electrodes for applying an

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electric field. Bulk modulators can handle large optical powers because the laser beam diameter can be on the order of the transverse dimension of the electrooptic (E/O) crystal instead of the very small diameter of a single mode waveguide. Also, the power lost entering, traversing and leaving bulk modulators can be quite small. The voltage required for good depth of modulation in these devices is usually hundreds to thousands of volts. This makes their use as high-speed communication modulators impractical.

One way to reduce the voltage required to provide good depth of modulation with a bulk modulator is to build a resonant cavity or etalon around the piece of electro-optic material. The resonance properties of the etalon amplify the effect of a voltage change applied to the electro-optic material.

Figure 1 shows an etalon. The input and output surfaces are polished flat and parallel. Dielectric coatings deposited on these surfaces make the transmission properties of the etalon substantially different from those of a simple piece of uncoated material. The transmitted power plotted as a function of the length of the etalon, or plotted as a function of the wavelength of the light incident on the etalon, goes through a series of maximums each time that the round trip phase of the optical light inside the etalon changes by 360 degrees. The optical phase is a function of the etalon length, the etalon index, and the laser light frequency. A phase change of 360 degrees is defined as either a round-trip path length change in the etalon equal to one optical wavelength, or to a frequency change of the light equal to one Free Spectral Range (FSR) of the etalon. A FSR of a solid etalon is given by

$$FSR = c/nL \qquad (1)$$

where c is the speed of light, n is the index of refraction of the etalon material, and L is the round-trip path length in the etalon.

A solid etalon made from a piece of electro-optic material can become an amplitude modulator by modulating the optical length of the etalon on and off a transmission peak. The electrooptic effect can be used to modulate the optical length. The amount of voltage required to vary the transmitted power from the transmission peak into the flat region between peaks can be much smaller than the voltage required to go a full free spectral range. For example, if the two mirrors have transmissions of 2% each, the modulation voltage for a 10 - 90% modulator would be 0.016 of that for one FSR. A problem with this configuration is that it is not possible to achieve a good
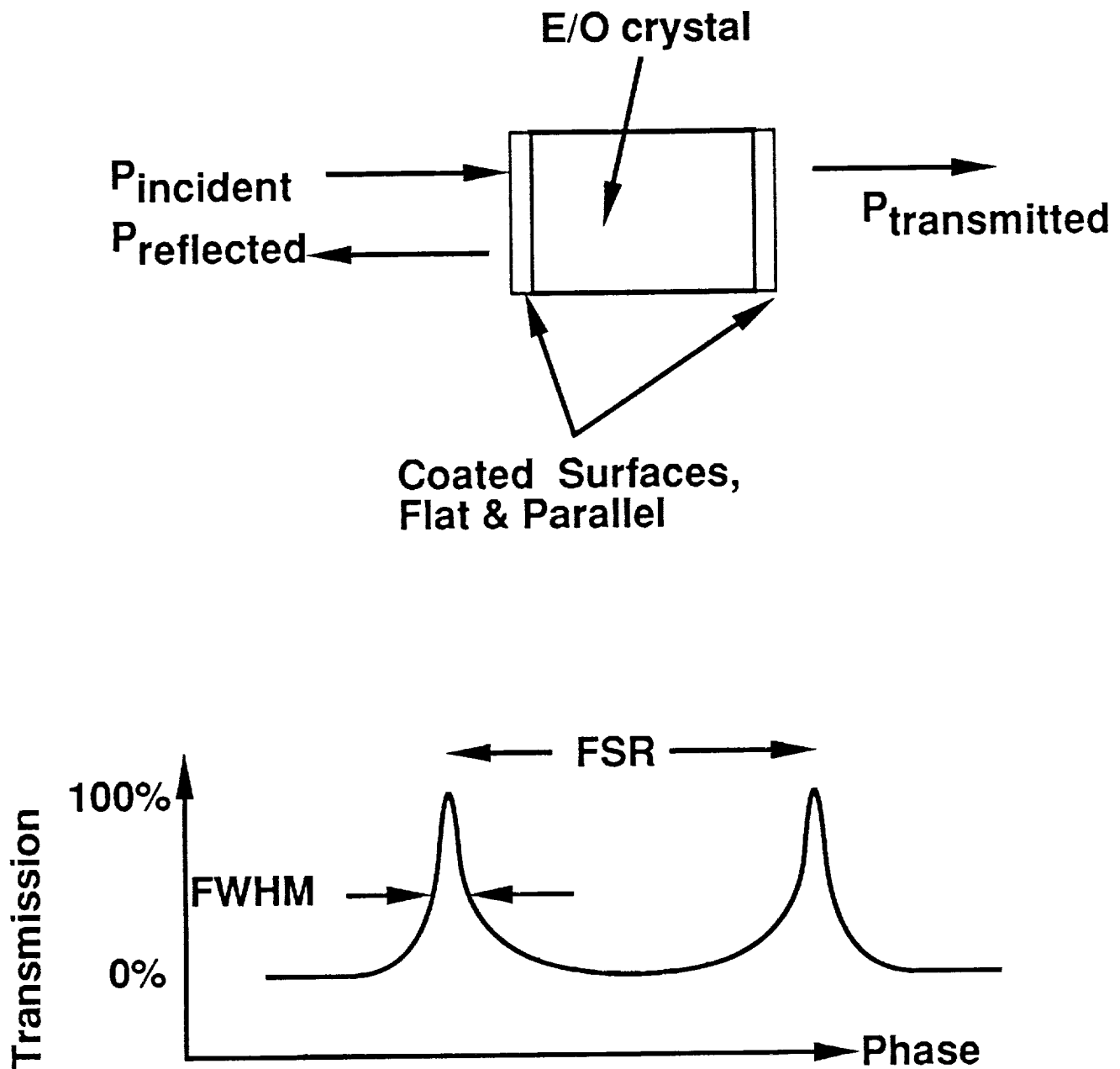
Figure 1. An etalon made of an electro-optic crystal can be used as an amplitude modulator. Partially-transmitting mirrors are coated onto the flat and parallel surfaces of the crystal. The transmission of the etalon is shown as a function of the optical phase between the mirrors. One free spectral range is defined as 360 degrees, or 2π radians, of phase shift.

extinction ratio and fast frequency response simultaneously.

The technique of using the resonance of an optical cavity to reduce the voltage requirement for an E\O modulator has not been popular in the past because the laser frequency stability, or linewidth, requirements on the light source are severe. Resonant enhancement devices need a very stable single frequency. Fortunately, the diode-pumped nonplanar Nd:YAG ring laser can easily meet the linewidth requirements.

If the output mirror in figure 1 is made as a 100% reflector and if the crystal has no losses, then 100% of the light would always be in the reflected beam independent of the phase change in the etalon, since there is no other place for power to go. What is very interesting is what the phase of this reflected wave is doing as a function of a 360 degree round trip internal phase change i.e. a scan over one FSR. This is shown in figure 2 where some finite bulk loss in the crystal has also been added. It is assumed that the second reflector is perfect, that the input mirror is a 95% reflector, and that the internal round trip loss is 0.5%. The reflected wave goes through a 360 degree phase shift over a scan of one FSR. 180 degrees of this phase shift occurs during that portion of the scan between the half power points of the resonance. The reflected power shows a dip because at resonance more power is coupled into the cavity and dissipated in the losses. Theory shows that the essential requirement to ensure that the reflected wave's E-field go through a 360 degree phase shift is that the input mirror have a greater transmission than the sum of the transmissions of the other mirrors plus the loss in the bulk of the E/O crystal.

A two-mirror version of such a modulator crystal using transparent electrodes is called a Gires-Tournois etalon [1]. Our configuration is shown in figure 3. It uses a three-mirror ring configuration with the output beam at 90 degrees to the input beam. The ring configuration eliminates reflections back into the laser whose output is being modulated. This is a very important feature.

The three-mirror cavity uses two flat total internal reflection surfaces and a spherical input/output mirror. The radius of curvature is chosen so that the ring cavity forms a stable resonator. The devices we fabricated were made from a single crystal of lithium niobate ($LiNbO_3$). The round trip optical path length is 13.2 mm and the thickness is 2 mm. The electrodes were gold plated onto the top and bottom of the crystal resulting in a transverse modulator configuration. In use the laser beam must be polarized perpendicular to these electrodes.
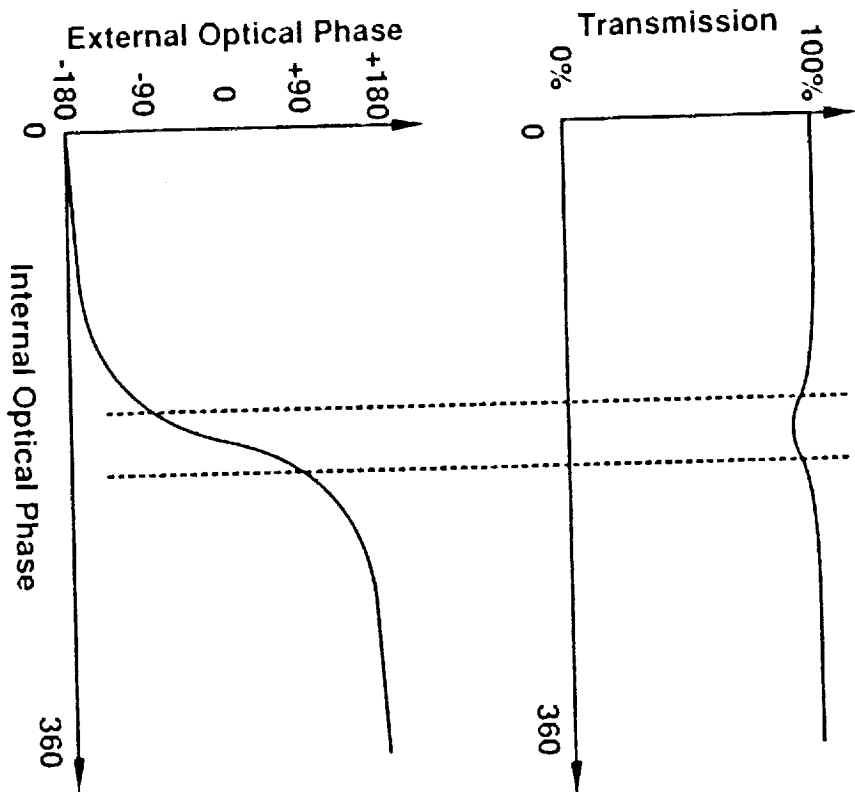
Figure 2. Amplitude and Phase of the light reflected from the etalon as a function of the internal phase change. Phase changes quickly near the resonance.
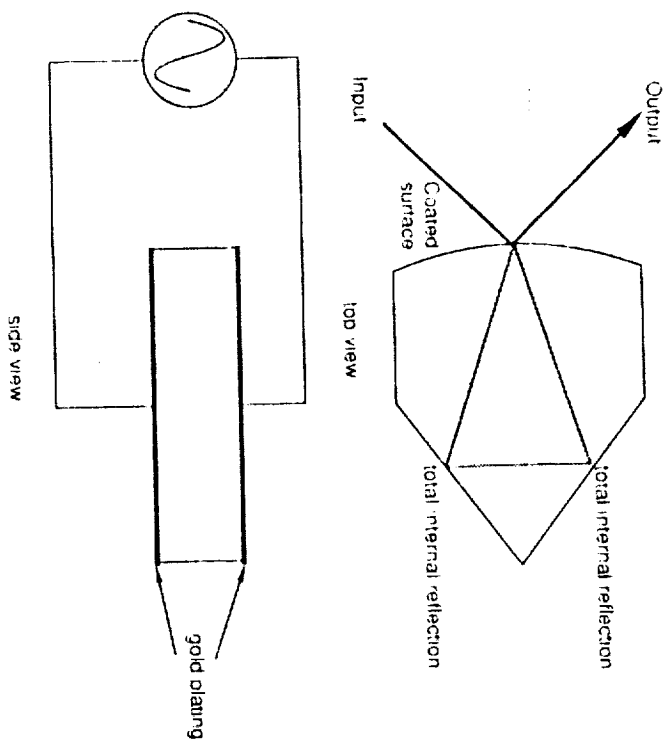

Figure 3. A resonant electro-optic phase modulator.

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Figure 4 shows a picture of the fabricated modulator crystal. To fabricate these monolithic rings, we designed and built special stainless steel jigs using concepts similar to those we use to fabricate our nonplanar ring lasers. All four of the modulators that we fabricated had the resonant ring path in the ideal center of the crystal indicating that the fabrication of thinner crystals, which will have lower modulation voltages, should be no problem.

The modulators we built all had the same shape, but were oriented differently with respect to the crystallographic axes of the $LiNbO_3$. For the orientation which gave the best results, the z-axis is perpendicular to the electrodes. This configuration makes use of the largest electrooptic coefficient, r_{33}. This configuration results in an electrooptic effect which is independent of the direction of the other two crystal axes. Two of the four modulators built used this orientation.

The other two modulators were made with the y-axis perpendicular to the electrodes. In this case the electrooptic coefficient is r_{22} which, at the high frequencies used for communication, is almost an order of magnitude lower than r_{33}. Also the higher r_{22} coefficient at low frequency is caused by the secondary piezoelectric effect which is not independent of the other two crystal axes [2]. The reason we even considered this configuration is that it was expected to have better thermal stability. The change in refractive index with respect to temperature of the ordinary wave in $LiNbO_3$, which is the one affected by r_{22}, is much less than for the extraordinary wave, which is affected by r_{33}. At higher finesse values when more power is coupled into the crystal losses, we were concerned that the resultant heating could cause undesired phase changes, which could be a problem.

Figure 5 shows the optical diagram of the setup used to test the modulators. This diagram also shows a way to make the phase modulator into an amplitude modulator. It is a Mach-Zehnder interferometer with the E/O phase modulator in one leg. The single-frequency laser is mode-matched into the modulator by lens L1. The two legs of the interferometer are formed by the first beamsplitter. A mirror with the same radius as the modulator was used in the passive leg for ease of modematching at the output. Lenses L2 and L3 collimate the two beams onto the output beamsplitter. A useful by-product of this system is the production of two output beams, which are complements of each other.

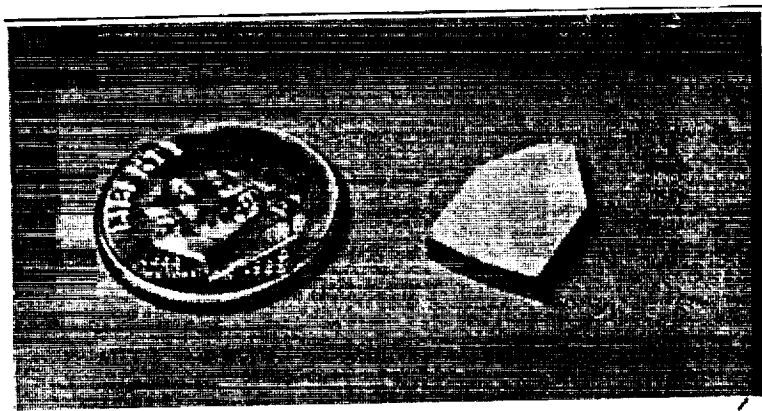The modulators we built were coated for use with 1.06

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Figure 4. The Lithium Niobate resonator to the right of the dime is twice the size (scaled linearly) of the modulator used in our Phase I work.
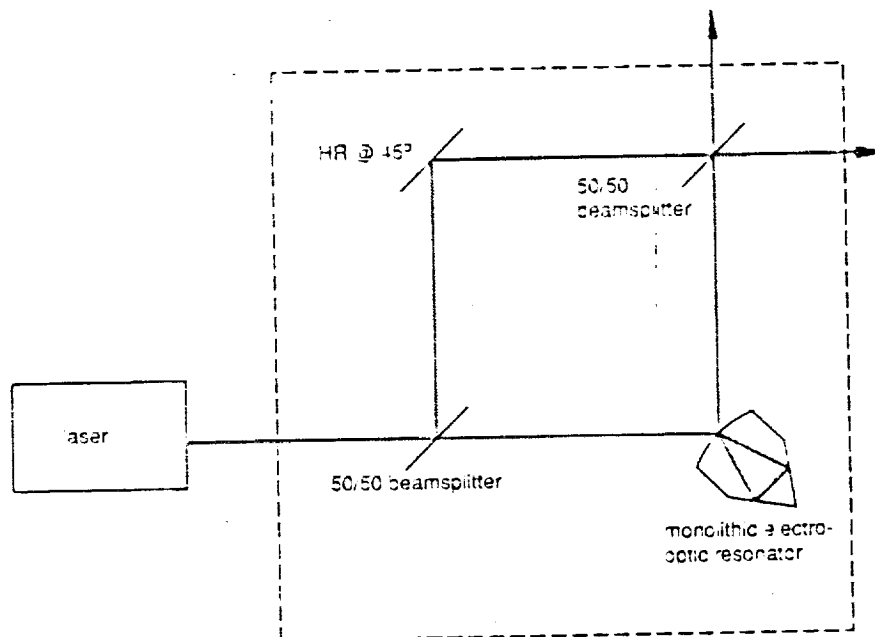

Figure 5. A phase modulator incorporated into a Mach-Zehnder interferometer becomes an amplitude modulator. The two outputs are are modulated with the opposite sign.

micron light. The coating on the phase modulator was an 80% reflector at 1.06 microns. Figure 6 shows a calculated amplitude and external phase response for the above modulator assuming a round trip crystal loss of 0.5%. 180 degrees of external phase shift about the center resonant point is obtained with 12.75 degrees of internal optical phase shift. This is equivalent to saying that the external phase shift is amplified by a factor of 180/12.75=14.1. The finesse of the modulator is 28.2. We have shown that the phase shift multiplication factor is always equal to half the finesse, for the case of external phase equal to 180 degrees. The amplitude variation around resonance is 4.9%.

The voltage required to scan a FSR, also defined as 360 degrees of external phase shift, is given by

$$V = (2 \ w \ t)/(r_{ij} \ n^3 \ p) \qquad (2)$$

where w is the wavelength of the light, t is the crystal thickness, r_{ij} is the appropriate electrooptic coefficient, n is the refractive index and p is the round trip path length. For $LiNbO_3$, n = 2.2 and r_{33} = 30.2 X 10^{-12} m/volt. From equation (2) we calculate that it takes 1064 volts to scan a FSR.

With a finesse of 28.2, the voltage change to switch 180 degrees (or light to dark with amplitude modulation) is theoretically 1064 volts / 28.2 = 38 volts. In the laboratory we measured 40 volts. The measured absorption dip at line center was about 6%. Thus, at least at low frequencies, our theory appears to be accurate.

The modulators with the y-axis perpendicular to the electrodes required 175 volts to produce a 180 degree shift. This is consistent with the ratio of the low frequency r_{33}/r_{22} coefficients. It should be noted that the difference between the low and high values of r_{22} is almost 2 while for r_{33} the difference is about 9%. Thus at high frequencies the y axis device should require 350 volts while the z axis device requires 40 volts x 1.09 = 44 volts.

The absorption dip for the y-axis device was 19%. This is larger than expected. We think this is due to the fact that all of these modulators were fabricated from crystals grown along the z axis. In $LiNbO_3$, as in many other crystals pulled from a melt, there is some level of striae perpendicular to the growth direction. If propagation is normal to the plane of the striae, the scatter losses are lower when the light is propagating in the plane of the striae. This low-scatter condition is

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Amplitude versus Modulation
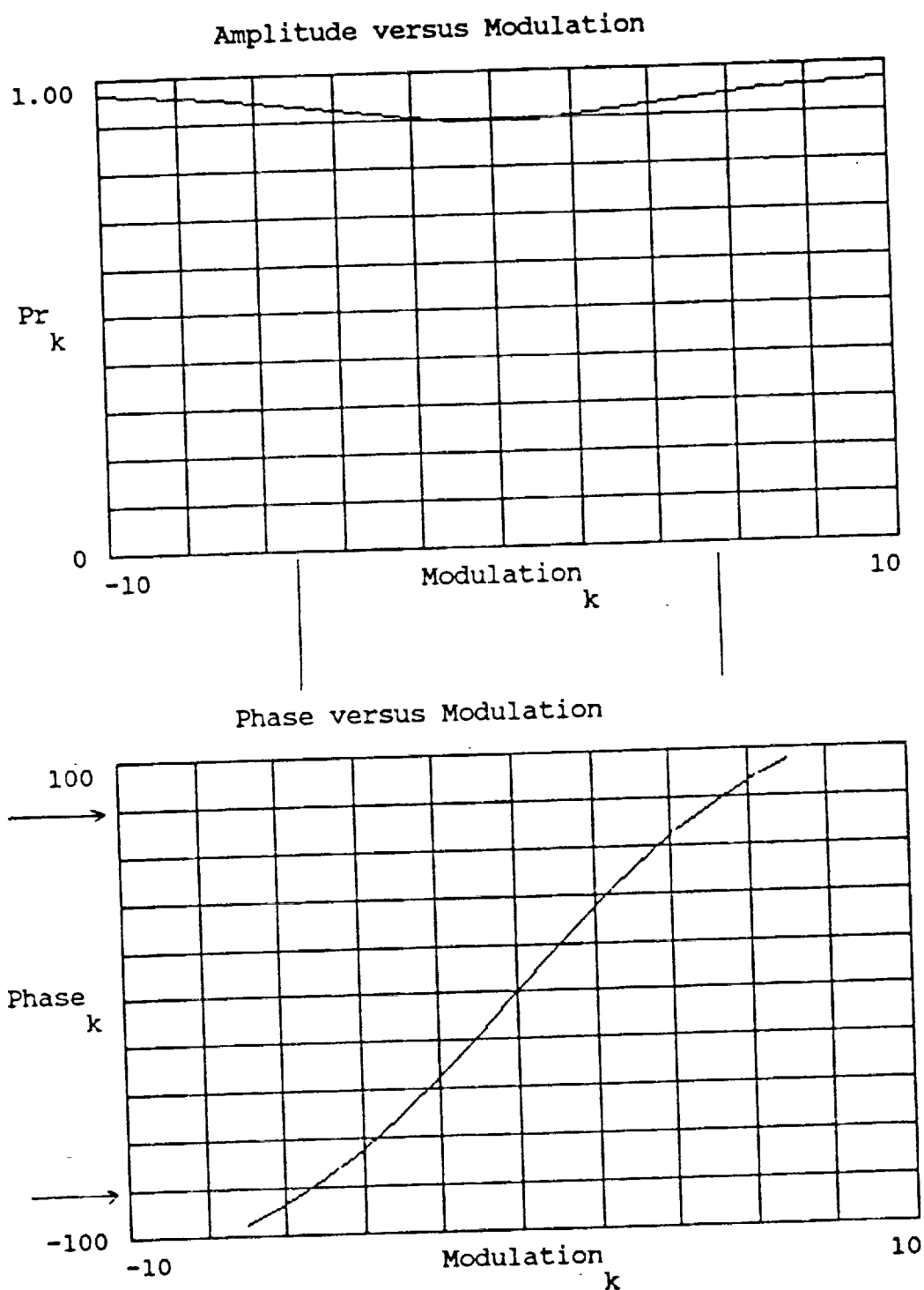

Phase versus Modulation

Figure 6. Upper plot is the theoretical reflectivity of
the resonant modulator, plotted as a function of the
internal phase shift in degrees. At all points more than
90% of the light is reflected. Lower plot is the external
phase shift, in degrees. plotted as a function of the
internal phase shift, in degrees.

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the case for the r_{33} modulators.

There was not enough time during the Phase I to complete an experimental study of the behavior of the modulators at high frequency. We did calculations and computer simulations to determine the possible limitations at high speed. Using a parallel plate model the capacitance of the modulator we fabricated is 4.4 pf which shouldn't be hard to drive. The impedance of a 4.4 pf capacitor at 1 GHz is 36 Ohms. This is not a difficult load to drive.

Characterizing the modulator as a lumped capacitor rather than as a distributed element will be inaccurate if the transit time of the modulation field across the modulator is significant relative to the duration of a cycle at the modulation frequency. The calculated transit time across the experimental modulator design is 0.1 nsec. This would not indicate problems at frequencies up to 1 GHz.

Optical cavity lifetime is also places limitations on high frequency response. The calculated cavity lifetime with the 80% reflector is 0.43 nsec. The reciprocal of this number is 2.3 GHz. Not knowing exactly what this number means with respect to digital modulation, we developed a one-dimensional finite-element computer model. The program divides the resonator into a few hundred elements. This division is along the direction of propagation of the beams - the transverse field distribution is assumed to be Gaussian. The amplitude and phase of the light in each element is stored. The program works by keeping track of what happens to light in each element in the few picoseconds which it takes to transit through the element. A major assumption is that all E/O-induced phase shifts happen instantaneously. This model could be modified to take into account the finite charging and discharging time of the capacitance of the modulator.

Figures 7 through 9 show the results of the model for the case of the modulators we fabricated. The graphs show the almost square input phase change and the resulting modulation of the output. Figure 7 shows a simulation for 300 Mbits/sec i.e. the shortest interval is 3.33 nsec. The output is a fairly reliable representation of the input. In figure 8 the minimum interval has been reduced to 2 nsec to represent 500 Mbits/sec. In this case the full 180 degree shift is not quite made. A one nsec interval is shown in figure 9. In this case only about 100 degrees of full shift is reached. In these cases the model assumes a 13.2 mm path length and an 80% output coupler.
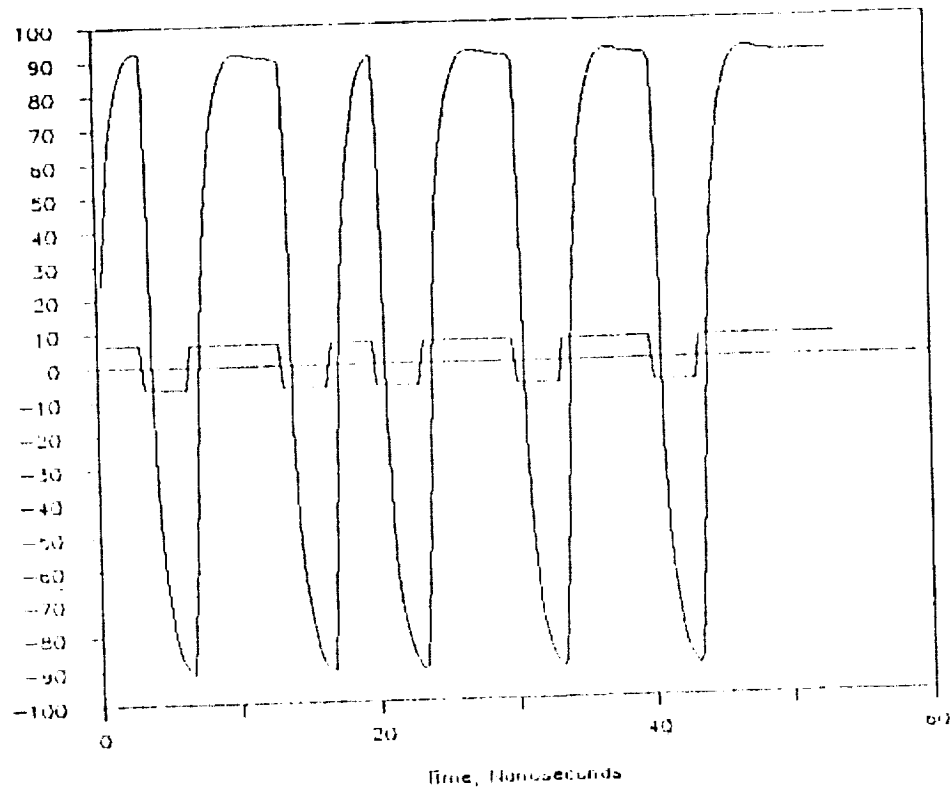
Figure 7. Theoretical plot of phase modulation at 300 MBit/Sec, for modulator used in Phase I. Full 180 degree shift is observed.
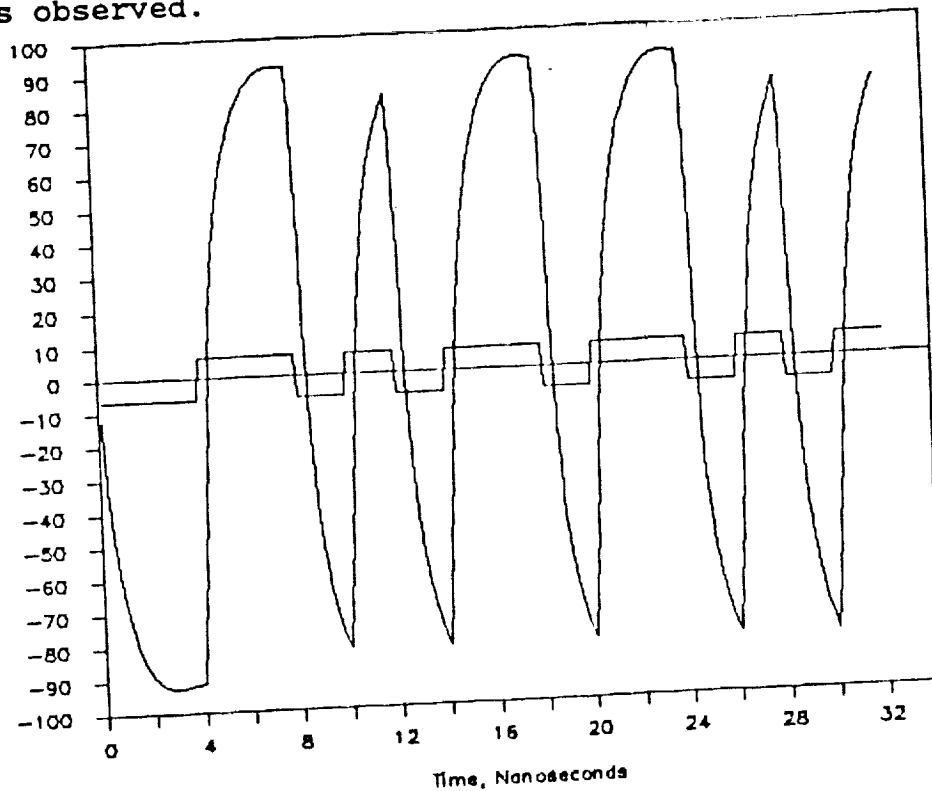

Figure 8. Theoretical plot of same modulator at 500 MBit/Sec. For bits of length 2 nsec, 180 degree phase shift is barely reached.
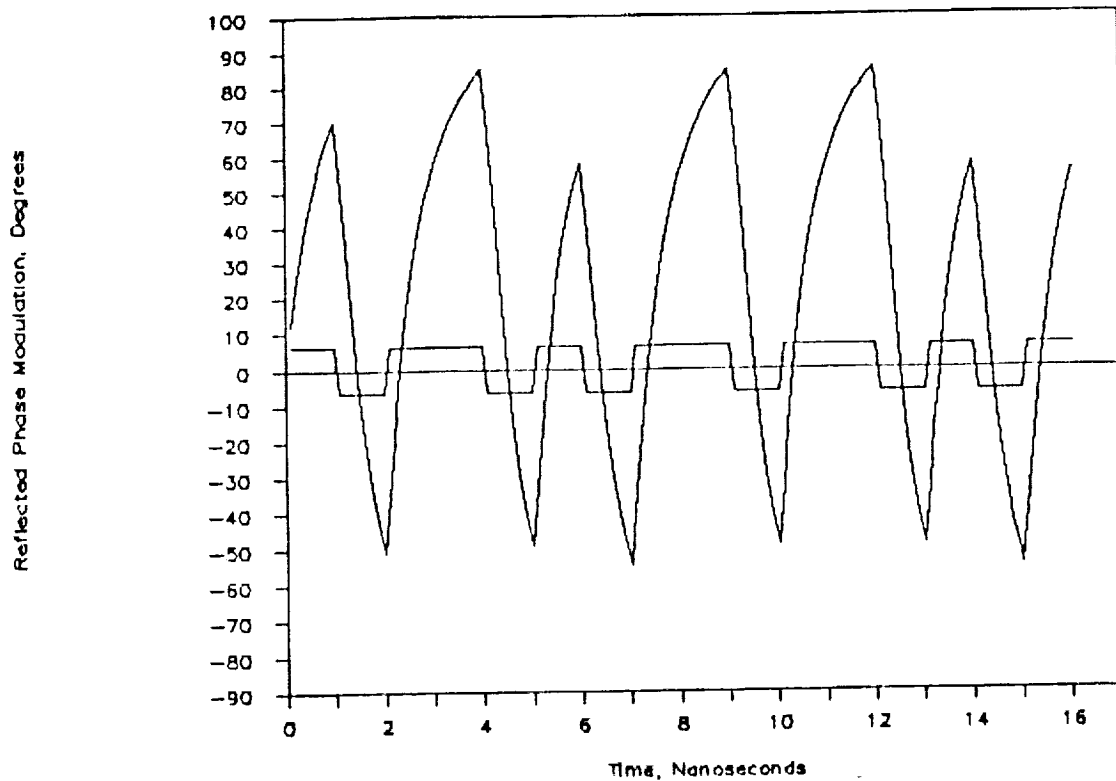
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Figure 9. At 1 GBit/Sec, the effect of finite cavity buildup time is seen clearly. 1-nsec bits do not have full 180 degree shift.

In actual use as a modulator, the frequency of the laser to be used with the modulator must be locked to the center of the resonance of the modulator. If it is to be used as an amplitude modulator, the interferometer must also either be actively stabilized or be designed for very high passive stability. The modulation frequency of transmitted information will probably be well above the tens of MHz. We propose that the band between DC and 1 to 100 kHz be reserved for the electronics which lock the laser to the resonators.

We did not have the time during phase I to lock the laser frequency to the modulator. We have successfully done the same thing with an external resonant doubler of MgO:LiNbO$_3$. This external resonant doubler has dimensions double those of the modulator. To lock the laser to the resonant doubler we put a 10 kHz dither on the LiNbO3 and used the absorption dip of the transmitted beam as a discriminant. This locking technique was fast and reliable. A number of other locking techniques have also been considered. We are confident that quite a number of techniques would work, and the best one will be the simplest.

The tradeoffs between speed, size and ease of fabrication of these modulators have been considered. The required voltage for 180 degree modulation can be reduced in two ways; increasing the finesse by reducing mirror

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transmission, and making the crystal thinner. The fundamental limits on thinning the crystal occur when the power density reaches a level where thermal or photo-refractive problems prohibit frequency locking. For our resonant doublers, which have a two to four times longer path, we have had no problems up to levels of 130 kW/cm^2 at 1.06 microns. If we want to modulate a one Watt beam, then the beam in the modulator must have a $2w_0$ spot size greater than 0.1 mm. This is the limit placed by thermal fundamentals. From a practical fabrication point of view, we could not fabricate crystals this thin. A thickness of 0.25 mm would be a challenge while 0.5mm would be no problem.

Increasing the finesse increases the cavity lifetime which reduces the maximum modulation frequency (f_{max}). Our computer model showed that an 80% reflector (finesse = 28) and a 13.2 mm path length indicated an f_{max} around 300 to 500 Mbits/sec. The cavity lifetime is not only a function of the output coupling but also the optical path length in the resonator. Figures 10 and 11 show the computer results for a modulator one half the size of the modulator we built but with the same 80% output reflector. The minimum time interval is 1 nsec. Figure 10 shows the phase out of the modulator and figure 11 shows the power amplitude out of one beam of the interferometer. Note the small overshoot that our model predicts.

A shorter optical path not only reduces the cavity lifetime but it also reduces the power absorbed into losses. However, the modulation voltage is inversely proportional to this path length. The capacitance is proportional to the area over the thickness.

Thus if we built a modulator exactly half the size of the current ones, and with the same mirror transmission, we would expect capacitance to be reduced to 1/2. Voltage for 180 degree external phase shift would be unchanged. Time delays due to transit times of the optical power or of the modulation signal would be reduced to 1/2. Since all critical time constants are halved, the maximum modulation rate should be doubled. For Phase II we propose to build modulators as small as possible.

Table 2 summarizes our work under this contract related to resonant modulators.

Table 2: Modulators Built and Tested in Phase I

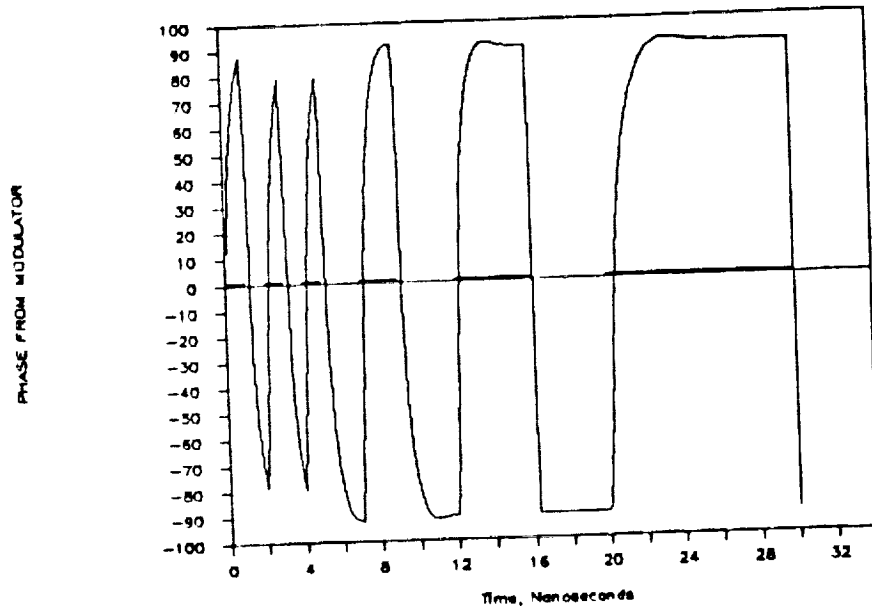| Material	Orient.	Volts for 180 degrees		Reflectivity
		Theory	Experiment	
LiNbo$_3$	r_{33}	38	40	94%
LiNbO$_3$	r_{22}	175	175	81%

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Figure 10.   Theoretical phase shift at 1 GBit/Sec from the
modulator proposed for Phase II, which is half the size of
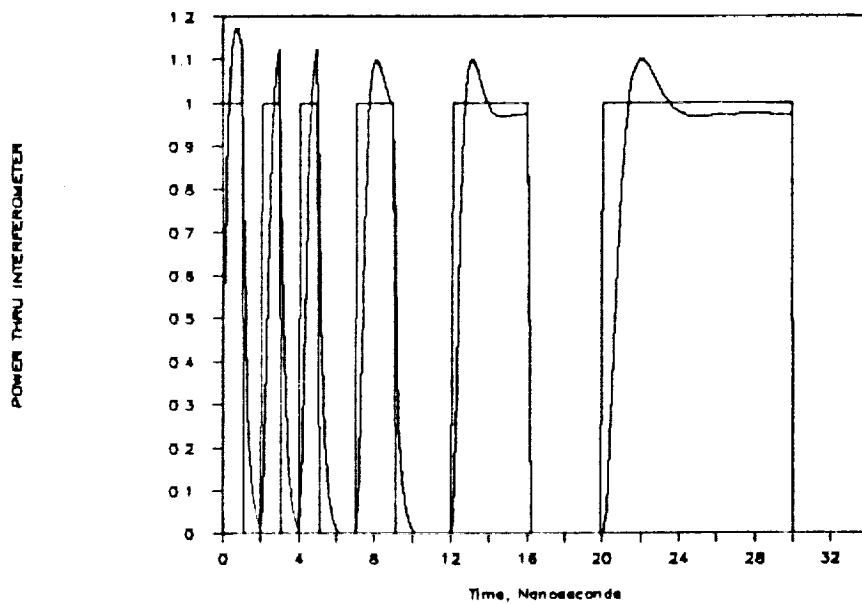the Phase I modulator.

Figure 11.   Theoretical amplitude modulation from Phase II
modulator.   1-nsec bits reach 100% power level.   Overshoot
is due to storage of power in resonator during period when
modulator passes through resonance.

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Possible reference lines

We made a search of the literature for atomic or molecular absorption lines which would be of use for long-term frequency locking of lasers. Long-term locking is of value for coherent communications. Coherent communication systems require that the transmitting laser and the receiving local oscillator be at very nearly identical frequencies. Once a link is established, this locking is not difficult, because the frequency difference between the lasers can be observed and controlled electronically. When establishing a link for the first time, or after an interruption, exactly-known frequency is helpful. The time needed to find and lock to the transmitted signal will be much reduced if the two lasers are initially at the same frequency. Precise absolute frequency control will also be of value to keep nearby channels from interfering.

There is quite a wealth of data on absorptions in the visible range. The near infrared has much less data. Diatomic molecules such as carbon monoxide or hydrogen fluoride have many absorption lines in the infrared. These lines are most strong near 5-10 microns and are of much less strength in the range from 1 to 2 microns.

A source of information on atomic transitions is "Tables of Spectral Lines of Neutral and Ionized Atoms," by A. R. Striganov [3]. We table below contains lines near the wavelength of solid state lasers.

Table 3: Atomic Lines near Laser Lines

Laser Material	Laser Wavelength	Atom	Ionization State	Atomic Wavelength	Energy Level
Nd:YAG	1.0641 um	N	II	1.0643981	13 eV
Nd:YAG	1.1225 um	He	I	1.12259	24 eV
Nd:YAG	1.3187 um	Cl	I	1.318258	11 eV
Nd:YAG	1.3381 um	Cl	I	1.338246	12 eV
Tm:YAG	2.0132 um	Cs	I	2.0140	3.3 eV
Ho:YAG	2.0975 um	Ar	I	2.09861	14 eV

All these lines could probably be found in appropriate electrical discharge tubes. The typical width of a line in such a tube is 1 GHz. With good technique, line centers can be found to within 1% of linewidth, or 10 MHz. This kind of stabilization might be useful for advanced coherent communications applications.

We chose not to pursue absolute stabilization in Phase II because we want to concentrate on modulation. The type of modulator we are proposing for Phase II could be used in coherent or direct detection systems. Absolute

stabilization is not a critical issue for the types of systems we propose.

Other laser lines

It would be valuable to identify several laser transitions which could be used for coherent communication. The existence of several usable wavelengths would permit multiple links to use the same spatial link, while not interfering.

There are a number of neodymium hosts which lase at wavelengths near, but not identical to, the Nd:YAG wavelengths. We are able to build monolithic ring lasers only with those which are in the garnet family of crystals. We built monolithic ring lasers from two garnets. Our experimental work with Nd:GGG and Nd:GSGG was disappointing. We observed low power, bad beam quality and high intensity noise. This makes us think that for the time being we should concentrate on the technologically well-developed material, Nd:YAG. The table below lists the wavelengths at which we have successfully built single-frequency Nd:YAG lasers, along with the power achieved. Only the entry for 1.06 microns was data produced under this contract. The other values have been achieved as part of Lightwave's commercial work.

Table 4: Single-Frequency Power from 4 Nd:YAG wavelengths

Wavelength, microns	Power, milliwatts
1.064	516
1.12	30
1.319	30
1.338	30

The separation between these four wavelengths is greater than the separation between different hosts operating on the same transition. This is advantageous, because the separation is large enough to allow wavelength multiplexing/demultiplexing with conventional multi-layer optical filters. Another line which may be possible is 0.94 microns. Five independent wavelength-multiplexed channels could thus be established using only Nd:YAG.

With effort in materials development, we are sure that additional garnet hosts could be used. For now we would prefer to make maximum use of the technically well-developed material Nd:YAG.

Phase I Conclusions

Under this contract, we built high-power

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single-frequency lasers at the wavelength of 1.06 microns, and attempted to build high-power lasers at 1.32 microns. We achieved 516 mW at 1.06 microns with a high noise level, and achieved 390 mW with low noise. We were unable to achieve high-power, single-frequency operation at 1.32 microns because of difficulties with coating fabrication. In trying to avoid oscillation at 1.34 microns, we got oscillation at 1.06 microns. The highest 1.32 single-frequency output to date is the 30 mW achieved routinely in the production of the 120-04 commercial single frequency laser by Lightwave.

The most exciting result from the work done under this contract is the bulk modulator with reduced voltage requirements. The resonantly-enhanced bulk modulator we invented, designed and built will permit 180 degrees of phase modulation at rates near a GHz. Optical damage limits should be well above the 1 Watt level. Many commercial and NASA applications exist for a single frequency laser with output powers in the 30 mW to 300 mW range, capable of phase and amplitude modulation at rates approaching one GHz, with drive requirements near 10 Volts.

For Phase II we will propose the design and construction of a small, self-contained diode-pumped nonplanar ring laser and modulator. Electronics would be designed and integrated into the system to automatically lock the laser frequency to the modulator resonance. An optional Mach-Zehnder interferometer could convert phase modulation into amplitude modulation. This Mach-Zehnder interferometer would be designed for high passive stability. If the stability were not adequate for reliable long-term use, then a second electronic loop would be built to hold the interferometer on resonance with the laser. The modulation voltage for 180-degree phase shift from the phase modulator, or equivalently for complete amplitude modulation, should be on the order of ten volts or less.

Lightwave feels that a phase II effort to develop an integrated single-frequency laser and modulator is justified not only for the development of a commercial product but also for potential use as an optical transmitter for space communications.

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